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Energy Procedia 37 (2013) 3503 – 3506

Energy

Procedia

GHGT-11

## Numerical prediction of the diffusion of CO<sub>2</sub> seeping from seabed in Ardmuchnish Bay

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### Abstract

To quantify the risk and impact of CO<sub>2</sub> seepage to the marine ecosystem, the Quantifying and Monitoring Potential Ecosystem Impacts of Geological Carbon Storage project is now undergoing in a bay in Scotland. In advance of the field experiment of this project, we conducted the numerical simulation of CO<sub>2</sub> seepage. From this numerical study, we predicted how CO<sub>2</sub> behave in the bay and how the condition of the sea changes.

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Selection and/or peer-review under responsibility of GHGT

*Keywords:* Sub-seafloor carbon storage; CO<sub>2</sub> seepage; Two-phase flow; Multi-scale ocean model

### 1. Introduction

To mitigate the global warming, it is necessary to reduce large volume of CO<sub>2</sub> released in the atmosphere. Carbon capture and storage (CCS) technology is one of the means for this purpose. However, sub-seabed storage has the risk of seepage due to the accidental failure of pipeline infrastructure or large diastrophism like a big earthquake. To estimate the impact of CO<sub>2</sub> seepage on marine ecosystem, the Quantifying and Monitoring Potential Ecosystem Impacts of Geological Carbon Storage (QICS) project is now undergoing at Ardmuchnish Bay in west Scotland. In this project, CO<sub>2</sub> gas is purposefully released at the sediment depth of about 11 m under the seafloor, the water depth of which is about 15 m, from May to June 2012. In this study, in advance of this experiment, we generated a level grid system imitating the topography of the bay, imposed significant tides, and conducted numerical simulations of CO<sub>2</sub> diffusion.

### 2. Methods

#### 2-1 Ocean Model

In this study, we used the Marine Environmental Committee (MEC) Ocean Model [1]. The MEC model consists of two main models: mesoscale hydrostatic and small-scale full-3D models.

### 2.1.1. Mesoscale Model

The governing equations of the mesoscale model are the Navier-Stokes (NS) equation and the continuity equation. The NS equation is approximated using the hydrostatic approximation:

$$\frac{Du}{Dt} - fv = -\frac{1}{\rho_0} \frac{\partial p}{\partial x} + \frac{\partial}{\partial x} \left( v_H \frac{\partial u}{\partial x} \right) + \frac{\partial}{\partial y} \left( v_H \frac{\partial u}{\partial y} \right) + \frac{\partial}{\partial z} \left( v_V \frac{\partial u}{\partial z} \right) \quad (1)$$

$$\frac{Dv}{Dt} + fu = -\frac{1}{\rho_0} \frac{\partial p}{\partial y} + \frac{\partial}{\partial x} \left( v_H \frac{\partial v}{\partial x} \right) + \frac{\partial}{\partial y} \left( v_H \frac{\partial v}{\partial y} \right) + \frac{\partial}{\partial z} \left( v_V \frac{\partial v}{\partial z} \right) \quad (2)$$

$$0 = -\frac{\partial p}{\partial z} - \rho g \quad (3)$$

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} = 0 \quad (4)$$

### 2.1.2 Small-scale model

In the small-scale domain, we adopted a full-3D model, in which we consider vertical flow. Therefore, Eq. 3 is replaced by the following:

$$\frac{Dw}{Dt} + fw = -\frac{1}{\rho_0} \frac{\partial p}{\partial z} + \frac{\partial}{\partial x} \left( v_{Ht} \frac{\partial w}{\partial x} \right) + \frac{\partial}{\partial y} \left( v_{Ht} \frac{\partial w}{\partial y} \right) + \frac{\partial}{\partial z} \left( v_{Vt} \frac{\partial w}{\partial z} \right) - \frac{\rho}{\rho_0} g \quad (5)$$

## 2-2 Two-Phase Flow Model

We simulated the behavior of the bubbles of CO<sub>2</sub> using a Lagrangian-Eulerian two-phase model. Details of this model are referred to Kano et al. [2].

## 3. Materials

### 3-1 Topography

Fig.1 shows the computational domain in this study, generated from the data of the topography of Ardmucknish Bay [3, 4].



Fig. 1 Computational domain.

### 3-2 Tides

Using the ocean tide model of [5], we obtained the amplitudes and phases of four significant tides at the computational domain site. These tidal elevations of the sea surface were imposed at the boundary of the computational domain as forcing boundary conditions.

## 4. Results and Discussion

The seepage rate of  $\text{CO}_2$  released under the seabed was set to be 80 kg/day. For the size of the initial bubbles, two cases were considered: 1 cm (Case 1) and 2 cm (Case 2) in diameter.  $\text{CO}_2$  was released from 1 May 2012 to 30 May 2012.

### 4-1 Dissolved $\text{CO}_2$

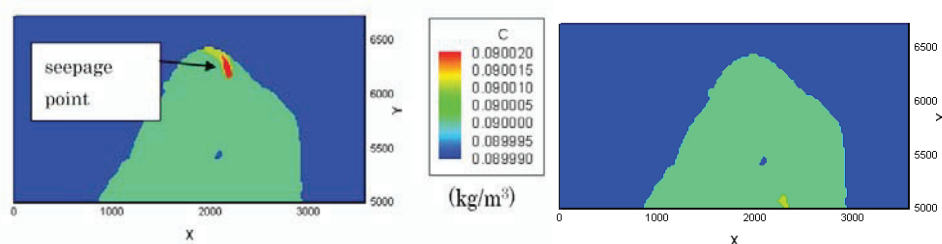


Fig. 2 DCO<sub>2</sub> in kg/m<sup>3</sup> at 3:45 on 20 May, high tide, (left) and at 10:00 20 May, low tide, (right) in Case 1

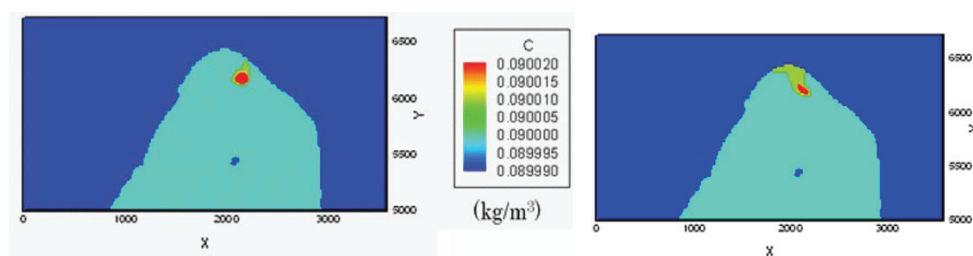


Fig. 3 DCO<sub>2</sub> in kg/m<sup>3</sup> in Case 1 at 16:10 on 20 May, high tide, (left) and in Case2 at 16:10 20th May, high tide (right).

Fig 2 shows the distribution of DCO<sub>2</sub> (kg/m<sup>3</sup>) at the depth of 11 m at the northeast of the computational domain at 3:45 on 20 May, high tide, and 10:00 20th May, low tide, in Case 1. From these results, we can see that DCO<sub>2</sub> goes to the north at high tide and turn left at the bay head due to the tidal residual current.

Fig. 3 shows the distribution of DCO<sub>2</sub> at the depth of 5 m at 16:10 May, high tide, in Case 1 and Case 2. DCO<sub>2</sub> concentration is larger in the case of small initial bubble size.

### 4-2 Gaseous $\text{CO}_2$ in Full-3D Model Domain

Fig.4 shows the distribution of bubbles in Case 1 and Case 2. From these results, we can see that most of bubbles leak to the air in Case 2. Therefore, Case 1 should give larger  $DCO_2$  than that in Case 2.

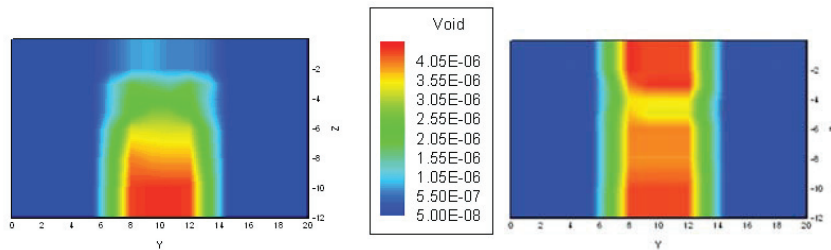


Fig. 4 Distributions of  $CO_2$  bubbles in the small-scale domain in Case 1 (left) and Case 2 (right).

#### 4-3 pH and $pCO_2$

Fig. 5 shows pH and  $\Delta pCO_2$  at the northeast of the computational domain at 16:10 on 20 May, high tide, in Case 1. pH and  $\Delta pCO_2$  are at most 0.004 and 0.15  $\mu atm$ , respectively.

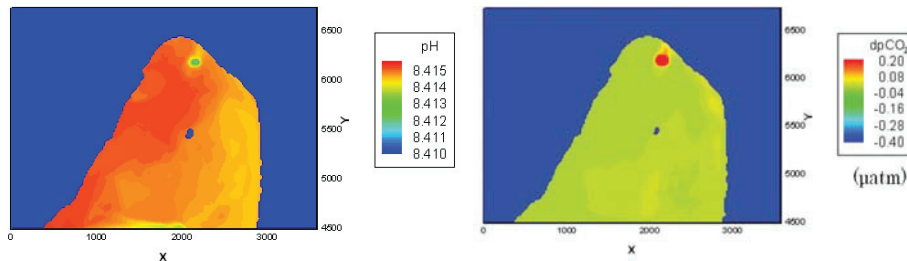


Fig. 5 Distributions of pH (left) and  $\Delta pCO_2$  (right) at 16:10 on 20 May, high tide.

### 5. Conclusion

$DCO_2$  goes to the north near the seepage point at high tide, so this position and timing are good to detect it. A mean bubble size of 1 cm gives larger  $DCO_2$  than that of 2 cm, because most bubbles leak to the air in the latter case. So, observations of bubble size and bubble behavior are necessary and very important. pH and  $\Delta pCO_2$  are at most 0.004 and 0.15  $\mu atm$ , when seepage rate is 80 kg/day. These values are too small to detect. So, it is better to increase seepage rate.

### References

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